Inverse Problems in Hydrologic Radiative Transfer

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Grant Number N000149910007

LONG-TERM GOALS

The long-term scientific goal of my research is to better understand the distribution of phytoplankton in the world's oceans through remote sensing their influence on the optical properties of the water.

OBJECTIVES

The long-term scientific goal of my research has been focused on the remote sensing of phytoplankton and other constituents from measurements water-leaving radiance propagated to the top of the atmosphere. Optically, phytoplankton and other constituents reveal their presence through their influence on the inherent optical properties (IOP's) of the water. The main effect of phytoplankton is to increase the absorption of light by virtue of the strong absorption by their photosynthetic (chlorophyll a) and accessory pigments. Other constituents, e.g., coccolithophores reveal theirs through high backscattering (large water-leaving radiance). Although techniques for measuring the absorption coefficient directly (e.g., in-situ AC9 measurements or in-vitro filter pad absorption) have become accepted by the scientific community, laboratory techniques for measuring backscattering are tedious and subject to error, and in-situ techniques for backscattering are in their infancy. Thus, there has been considerable effort devoted toward indirectly inferring these IOP's by virtue of their influence on the apparent optical properties (AOP's), e.g., the diffuse reflectance of the water (the color of the water) or the downwelling irradiance attenuation coefficient. These AOP's are perhaps the most frequently measured quantities in hydrologic optics. Clearly, interpretation of such observations requires a detailed understanding of the influence of phytoplankton on the IOP's and their link to the AOP's.

Although the research reported here is centered on deriving the IOP's from measurements of the AOP's, which is important in that IOP's determined from AOP's are, by definition, sampled at a scale appropriate for radiative transfer and for remote sensing. A secondary focus has been to try to understand the influence of particle shape on light scattering by marine suspensions. For this, we chose to attempt modeling the scattering of detached coccoliths of *E. huxleyi*.

APPROACH

In the mid 1990's the PI and coworkers developed techniques for retrieving the optical properties (single scattering albedo and scattering phase function) of aerosols from measurements of sky radiance

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2003**	2. REPORT TYPE	3. DATES COVERED **00-00-2003 to 00-00-2003**

4. TITLE AND SUBTITLE **Inverse Problems in Hydrologic Radiative Transfer**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Department of Physics,,University of Miami,,Coral Gables,,FL, 33124**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The long-term scientific goal of my research is to better understand the distribution of phytoplankton in the world's oceans through remote sensing their influence on the optical properties of the water.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

over the oceans [*Wang and Gordon*, 1993; *Gordon and Zhang*, 1995; *Zhang and Gordon*, 1997a, 1997b; *Cattrall, Carder, and Gordon*, 2003]. These were the basis for development of algorithms for inverting irradiance and/or radiance profiles in the water to obtain profiles of the absorption coefficient, a, and the backscatterinng coefficient, b_b. The algorithms are iterative in nature with the radiative transfer equation (RTE) solved during each iteration using trial IOP's. The key was conceiving a simple method of improving the estimated IOP's after each iteration by comparing the predicted and measured AOP's. When the latter agree within experimental error, the IOP's were deemed to be those of the medium.

For the study of light scattering by irregularly shaped particles, the discrete-dipole approximation [*Draine and Flatau*, 1994] was used, and the coccoliths were modeled as disk-like particles.

WORK COMPLETED

Table 1 provides a summary of the inverse problems that have been examined during the course of this study. These are detailed in a series of papers. The first paper reported development of inversions for homogeneous media with elastic scattering [*Gordon and Boynton*, 1997], the second extended the development to elastically-scattering vertically-stratified water bodies [*Gordon and Boynton*, 1998], the third treated inversion in the presence of the interfering effects of Raman scattering into the spectral band of interest [*Boynton and Gordon*, 2000], and the fourth, provided an improvement to the *Gordon and Boynton* [1998] algorithm for clear water (i.e., waters in which scattering by the water itself makes a significant contribution to $b_b(z)$, where z is depth) [*Boynton and Gordon*, 2002]. For a complete program of AOP inversion in natural waters, the only process we have overlooked is fluorescence, i.e., inelastic scattering into a given band of wavelengths from all shorter wavelengths. A method for solving this problem was provided by *Gordon* [2001] and applied to simulated data by *Boynton and Gordon* [2002].

Table 1. ***Matrix of Inverse Problems Relevant to Hydrologic Optics***

Problem	Water Body	
	Homogeneous	Stratified
Elastic (Depth = ∞)	✓	✓
Elastic (Depth < ∞)	✓	☹
Raman (Depth = ∞)	✓	✓
Fluorescence (Depth = ∞)	✓	✗

✓: Inverse solution completed
✗: Inverse solution not likely to be possible
☹: Planned approach failed

A theoretical study modeling light scattering by detached coccoliths as disk-like structures was carried out by *Gordon and Du* [2001].

Finally, as a confluence of our work on inverse methods and coccolith scattering, during the current reporting period we used the inversion methods that we developed to retrieve $b_b(z)$ as a function of wavelength and coccolith concentration by inverting irradiance data taken in intense coccolithophore blooms. A paper describing this effort is in preparation.

RESULTS

The entries in Table 1 summarize the results of our study on inverse methods in hydrologic optics. Typically, the inversions provide IOP's that reproduce the input AOP's almost exactly or , with field data, within experimental error. The check marks indicate the completion of an inversion method and, except for the case of fluorescence, a successful application to field data. The inversion technique we developed for fluorescence [*Gordon*, 2002, *Boynton and Gordon*, 2002], although functional with synthetic data, is very unstable as inversion in the presence of fluorescence is ill-conditioned. The problem can be solved (at least by our techniques) only when the fluorescence is strong — a situation not encountered in the natural environment. Initially, we believed that we had found a viable approach to inversions in stratified waters in which the bottom made a significant contribution to the upwelling light field. Unfortunately, we were unable to separate bottom reflection from backscattering, e.g., from a layer of particles just above the bottom, and this problem remains unsolved.

Our inversion of $b_b(z)$ as a function of wavelength and coccolith concentration in an intense coccolithophore bloom yielded a backscattering spectrum that was similar to one of the *Gordon and Du* [2001] models — most complex shape studied (the "fishing reel"). Figure 1 shows an SEM image of a detached coccolith (left panel) along with the "fishing reel" model (right panel), which can only approximate the gross structure of the particle. Figure 2 compares the spectral variation of the retrieved backscattering coefficient in the surface layer (red lines) with that predicted for the "fishing reel" model. The most interesting aspect of the comparison is the increase in scattering at wavelengths greater than 550-600 nm observed in both the model and the measurements. This increase in backscattering is due to constructive interference between rays internally reflected by the two plates (resonant scattering). Finally, although the spectral variation of b_b is well reproduced, the absolute magnitude of the backscattering on a per coccolith basis is smaller (~ factor of 2) than observations, and on a per calcite basis is somewhat higher than field measurements.

IMPACT/APPLICATIONS

The AOP inversion algorithms that were developed under this grant provide realistic profiles of *a* and b_b. The research also shows that although backscattering by disk-shaped objects is very dependent on morphology, it can be understood, and that models of irregularly shaped particles for light scattering by marine particles show some promise for understanding scattering properties of suspended particles.

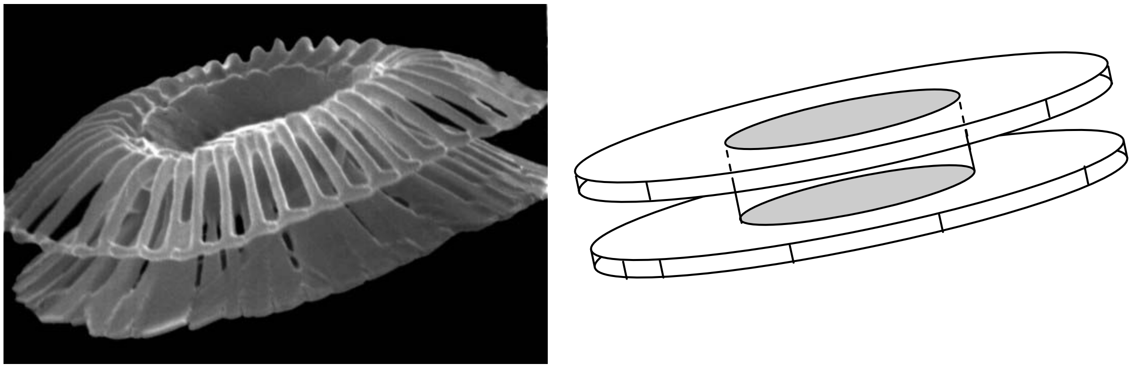

Figure 1. SEM image of a detached coccolith from E. Huxleyi (left panel). Fishing reel model of the coccolith resembling two washers of outside diameter **(2.7 μm)** *separated by a small gap* **(0.3 μm).**

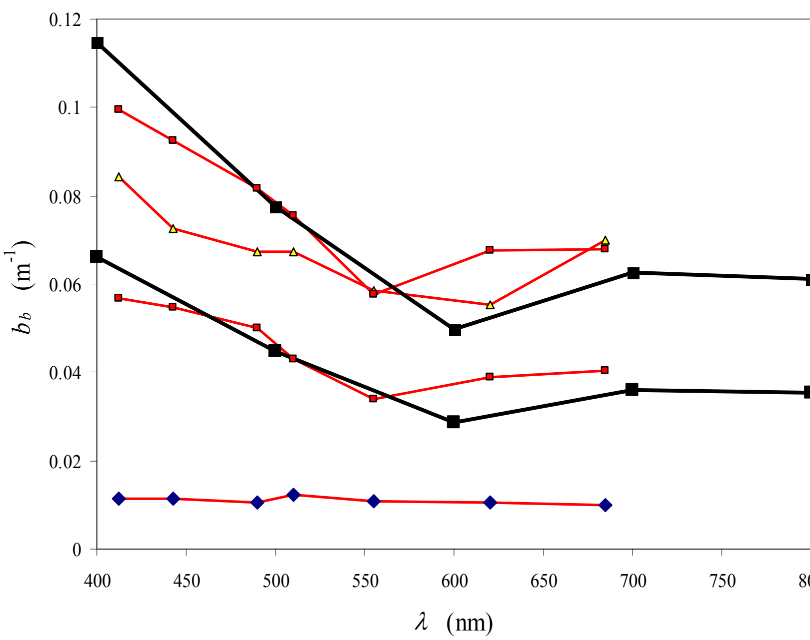

Figure 2. Comparison of the spectral variation of the retrieved backscattering coefficient in the surface layer (red lines) with that predicted for the Gordon and Du [2001] "fishing reel" model. The most significant aspect of the comparison is the increase in scattering at wavelengths greater than 550-600 nm observed in both the model and the measurements

RELATED PROJECTS

We are collaborating with A. Morel to apply our irradiance inversion algorithm to analysis of the OLIPAC data set and with the T.J. Smyth (PML) in applying our algorithms to data acquired in coccolithophore blooms to further delineate their optical properties. We have also been collaborating with R. Leathers (NRL) in comparing retrieval algorithms operating on irradiance data from the Gulf of California.

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HONORS/AWARDS/PRIZES

NASA Group Achievement Award 2002 to H.R. Gordon as part of the MISR Science Team.

Aqua Outstanding Teamwork Award 2003 (NASA) to H.R. Gordon for work on the MODIS Science Team.